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Low-order Wavefront Sensing Architecture and Results Summary

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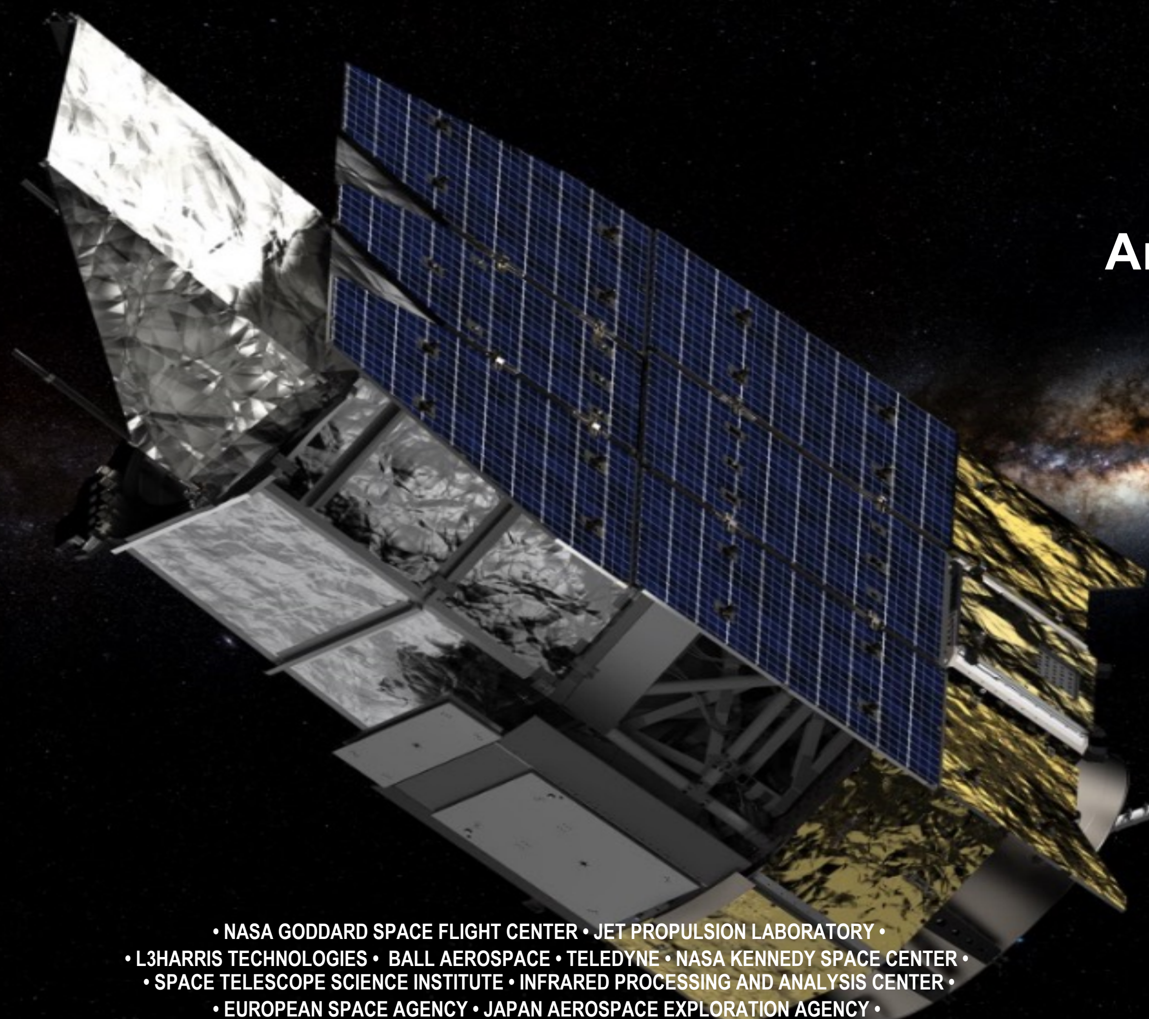

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Outline

- Optical context for LOWFSC
- Estimator construction
- Tip-tilt nonlinearity
- Performance requirements verified by test
- Performance requirements verified by analysis

Contributors to design and analysis (not including hardware and software implementation):

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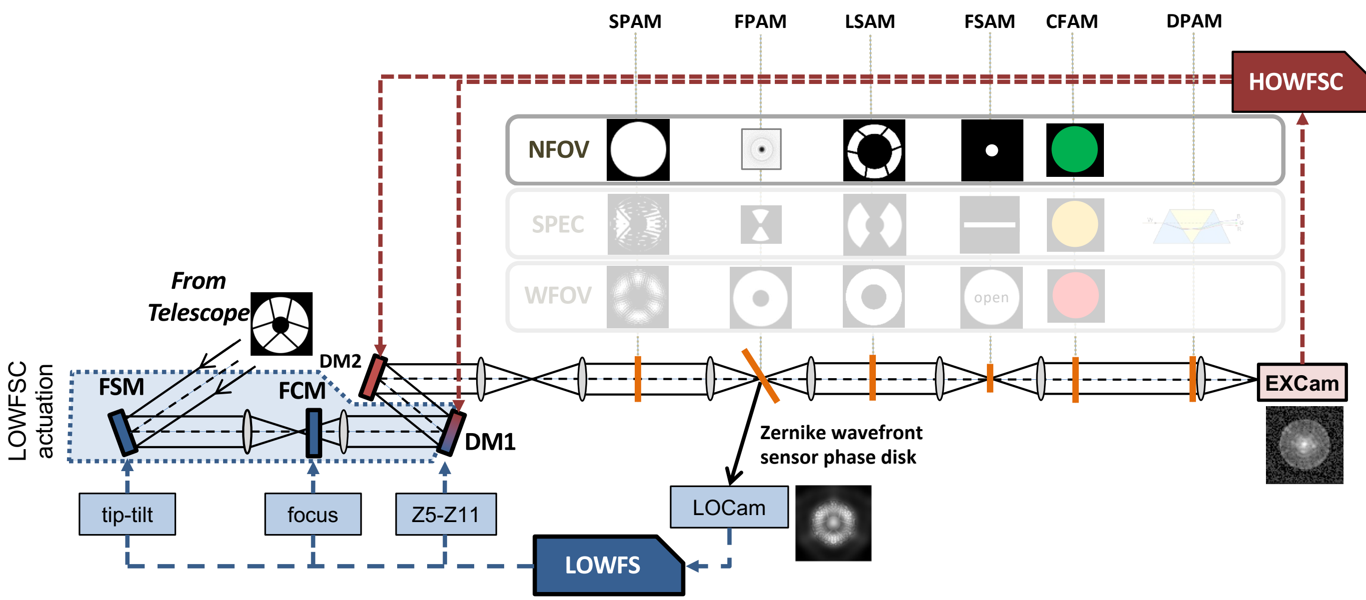
CGI LOWFSC hardware and context

actuate:
- FSM
  - tip-tilt
- FCM
  - focus
- DM1
  - astig ×2
  - coma ×2
  - trefoil ×2
  - spherical



LOCam frames at 1 kHz
- 0.1 Hz summing for Z4-Z11

tip-tilt cutoff frequency 20 Hz
Z4-Z11 cutoff frequency 0.016 mHz

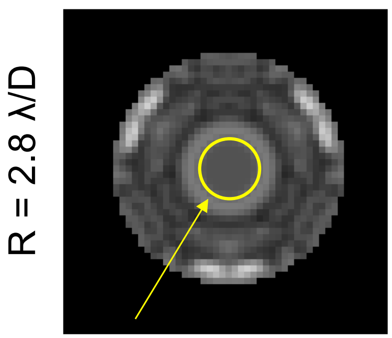
1. LOWFSC stabilizes incoming wavefront
- LOWFSC does not reduce CGI entrance pupil WFE
- LOWFSC feedback is continuous and real-time (millisec latencies, high flux)
- LOWFSC by itself does not enhance contrast
- LOWFSC enables HOWFSC to perform fine control that produces deep contrast
  - HOWFSC uses ground-in-the-loop, HOWFSC is set-and-forget
- LOWFSC enables long observations without losing deep contrast

2. LOWFSC enables star acquisition
- Roman slews leave observatory within ~ few arcsec of desired pointing
  - tolerance for centration on FPM is ~ mas
- CGI refines pointing to be within capture range of LoS loop and closes loop

LOWFSC Zernike mode morphologies

at FPM:

HLC FPM dielectric thickness pattern, 0 – 1.5 μm thick



PSF FWHM

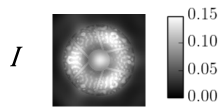
no quantitative consideration for LOWFSC in design of dielectric pattern; not a simple Zernike spot!

FPM ← source image

LOCam → pupil image

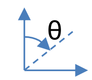
50×50 pixel LOCam pupil images (intensities) from model

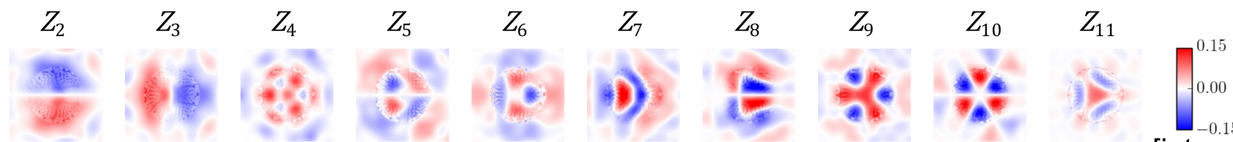
shown in LOCam orientation



reference LOWFSC image

(input pupil=1)





FSM FCM DM1

calibration delta-intensity images

- HLC input wavefront is very non-flat (PV ~ λ)
- FPM does not have simple morphology
- CGI does not use “traditional” Zernike Wavefront Sensor capability to measure wavefront phase directly

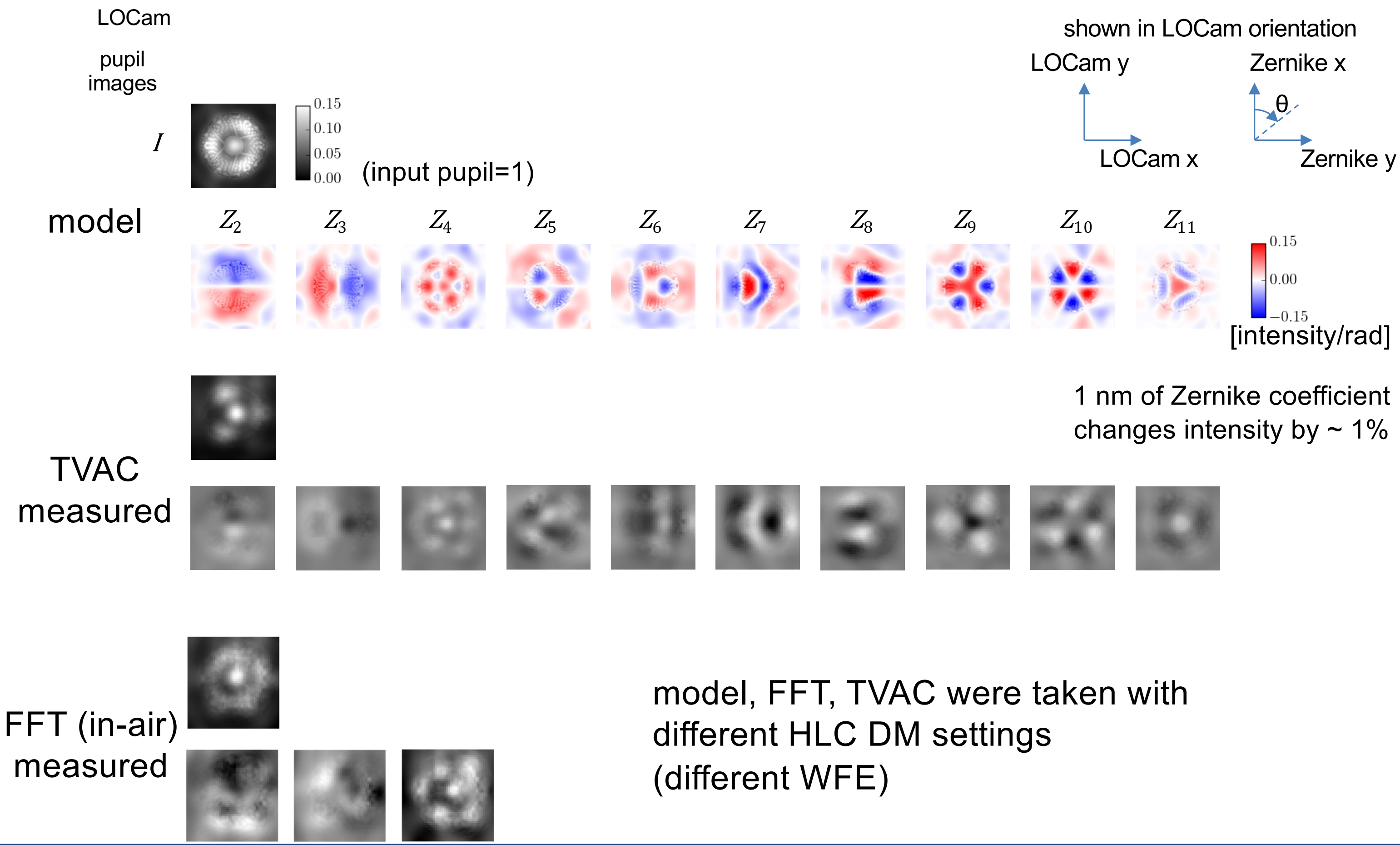
imperfect analogy with ZWS

HLC LOWFSC morphologies

nonquantitiative morphological match between model and measured is similar, but with fine-scale differences

these model results have not been updated with the observed CVS + NKT illumination spectrum

- morphologies evolve significantly with wavelength
  - 510 – 640 nm
- CVS + NKT is redder than stellar spectrum

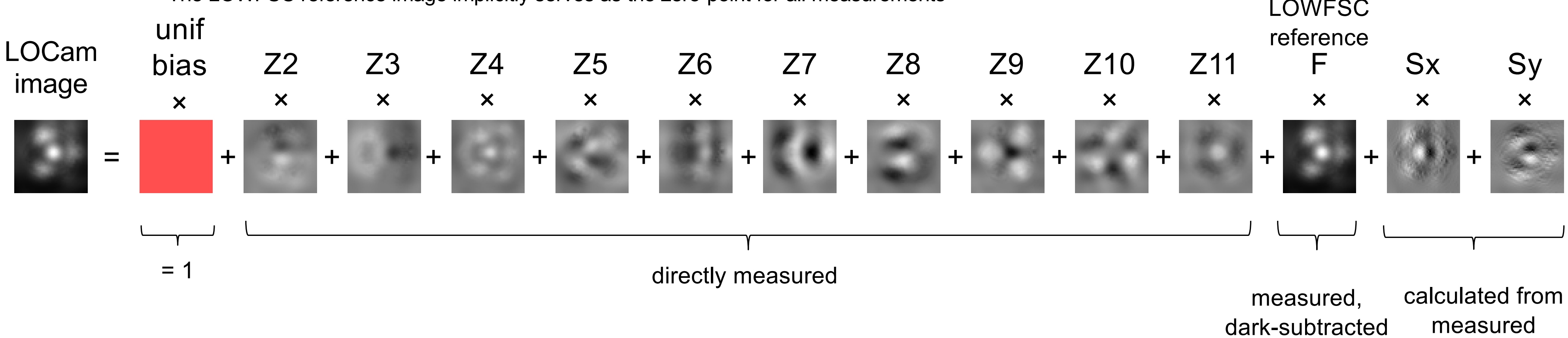


1 nm of Zernike coefficient changes intensity by ~ 1%

model, FFT, TVAC were taken with different HLC DM settings (different WFE)

construction of an estimator (1)

- LOWFSC estimator is a matrix-vector multiply operation that acts on every LOCam frame (at 1 kHz)
- the estimator determines coefficients to spatial modes, using a linear least-squares fit, to best describe the pixel-by-pixel values in the new LOCam frame
- in addition to 10 Zernike coefficients (Z2 – Z11), include coefficients for 4 other modes:
  1. uniform camera bias (+1 for every pixel)
  2. dark-subtracted LOWFSC reference image (variable to account for flux calibration errors or flux changes, and establish zero-points)
  3. LOCam-x shear of dark-subtracted LOWFSC reference (camera stability separate from coronagraphic optical train)
  4. LOCam-y shear of dark-subtracted LOWFSC reference
  - additional terms do not correspond to controls, but separately solving for them avoids misinterpreting benign errors / disturbances as control inputs affecting the coronagraphic optical train
    - The LOWFSC reference image implicitly serves as the zero-point for all measurements



all but 1 of estimator inputs are empirically measured

construction of an estimator (2)

- Each 50×50 pixel array in the decomposition is vectorized into a 2500-element pixel vector, and all these vectors are stacked into a 2500×17 matrix
  - 3 “unused” columns are all zeros
  - this matrix is a Jacobian, with elements $\partial I_j/\partial c_i$ the change in intensity at pixel j per change in coefficient i

  Zmm = $[\partial I_j/\partial c_0 \; \partial I_j/\partial c_1 \; \ldots \; \partial I_j/\partial c_{16}]$

  c_0 is uniform bias, $c_1 \ldots c_{10}$ are Z2-Z11 coefficients, c_{11} is flux, c_{12}-c_{13} are x- and y-shear
- The Moore-Penrose pseudoinverse of Zmm is denoted P

  $P = Zmm^{\dagger}$
  - P is a 17x2500 matrix
- The per-frame dark subtraction is calibrated by calculating a vector

  Q = -P • (LOWFSC reference image before dark subtraction)
- For every LOCam frame A (vectorized into 2500 pixels), in real-time, a vector of coefficients is determined by

  c = P A + Q
- c is a linear least-squares fit of intensity changes w.r.t. the LOWFSC reference image, with the changes decomposed into the empirical modes the estimator was trained to

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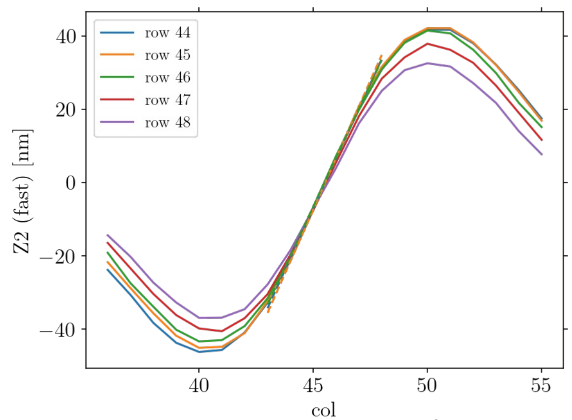
tip-tilt nonlinearity

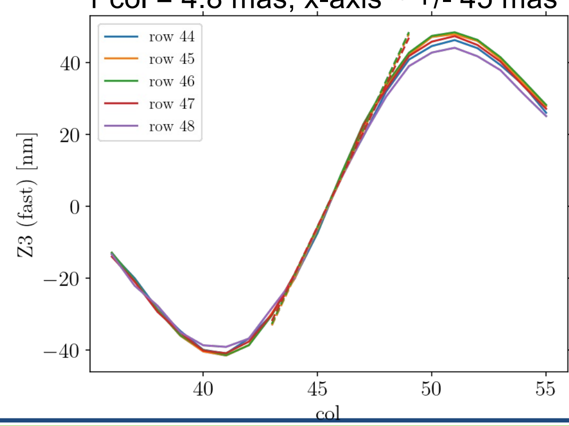
ROMAN CORONAGRAPH

- Tip-tilt estimation (Z2-Z3) is sufficiently linear for feedback to LoS control
  - Tip-tilt residuals < 1 mas rms / axis when LoS loop is closed
  - nonlinearity of Z2-Z3 estimates is < 10% over +/- 10 mas
- Acquisition requires reliable LOWFSC capture over 80 mas radius
  - Z2, Z3 nonlinearities significant with zero-crossings and sign errors in that range

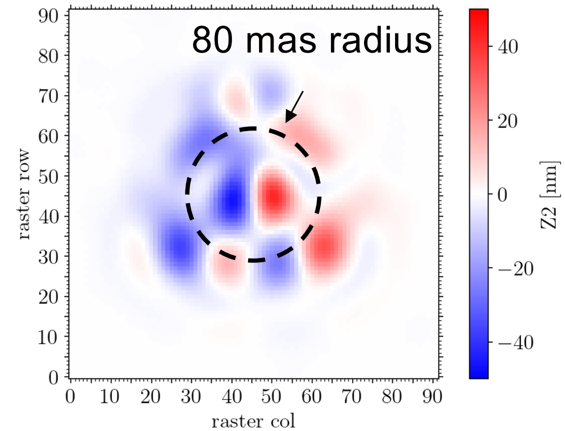
PSF locations on FPM cross-sections at small offsets

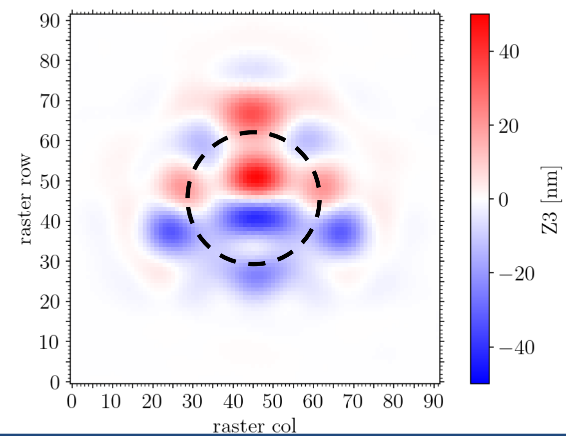


1 col = 4.8 mas; x-axis ~ +/- 45 mas



NOT pupil images / LOCam images
Z2 estimates for PSF across entire FPM





tip-tilt nonlinearity is significant for star > 10 mas off-center

4.8 mas / row or col; 80 mas = 17 rows or cols

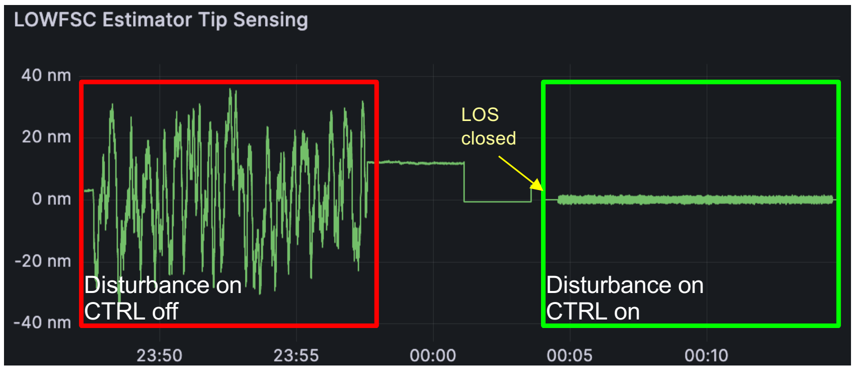
performance requirements verified by test

- Top-level LOWFSC performance requirements verified by test in TVAC:
  - Cutoff frequency for tip-tilt rejection
  - Cutoff frequency for focus control rejection
  - Cutoff frequency for Z5-Z11 (“Zernike loop”) rejection
  - LOWFSC capture range (80 mas radius, last step of acquisition)

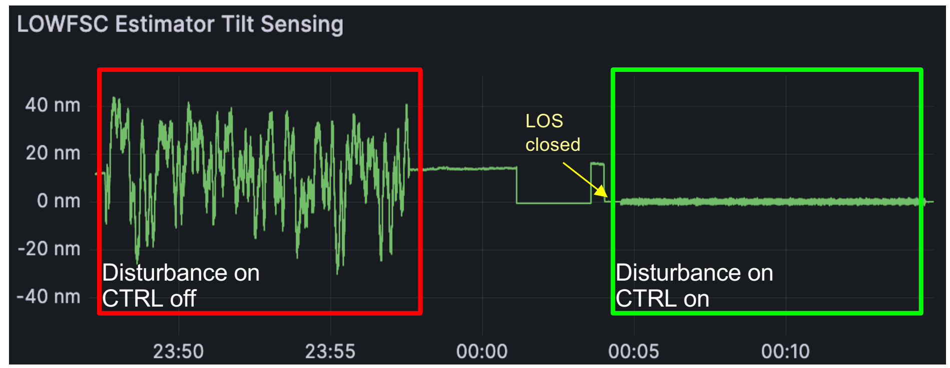
LoS control (tip-tilt)

jitter mirror outside CGI introduced pre-determined disturbance profiles

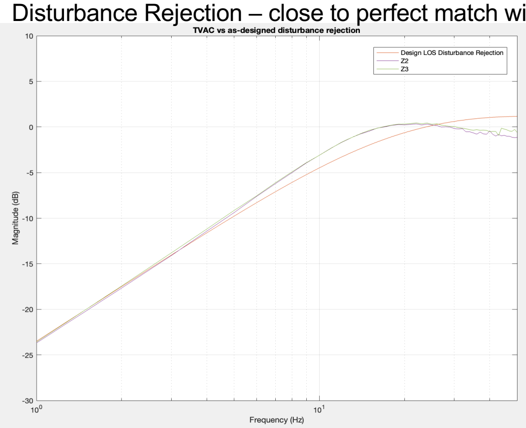
Z2 (100ms avg)

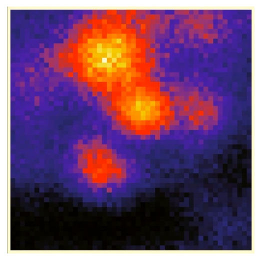


Z3 (100ms avg)



Disturbance Rejection – close to perfect match with design:

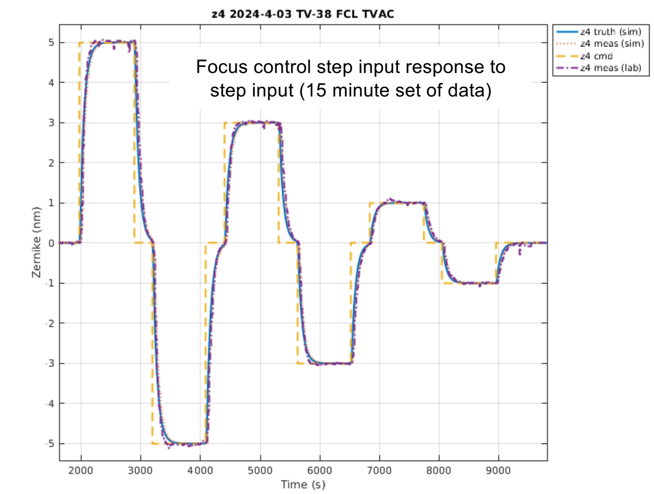


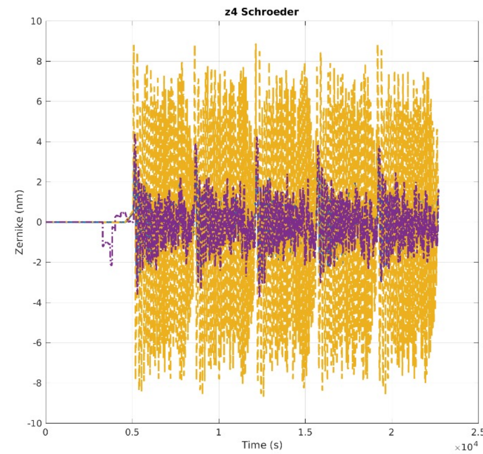


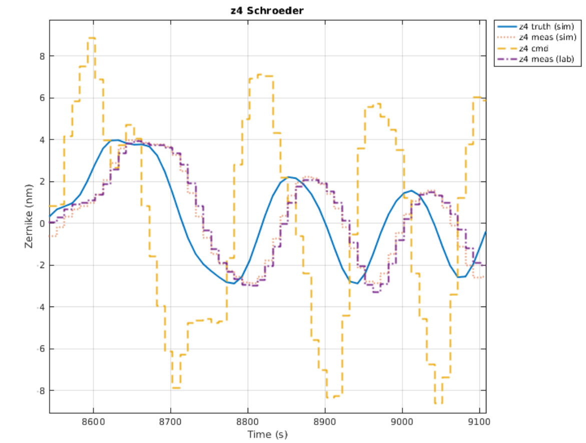
Sample disturbance rejection movie of LOCAM images (loop closed at 1.6 second mark)

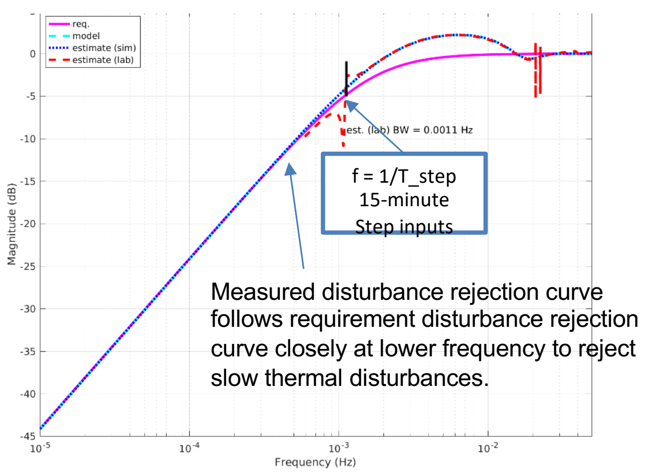
Requirement	CBE		Margin (%)
	x	y	
1.0 mas	0.45 mas	0.31 mas	55

Z4 (focus) rejection

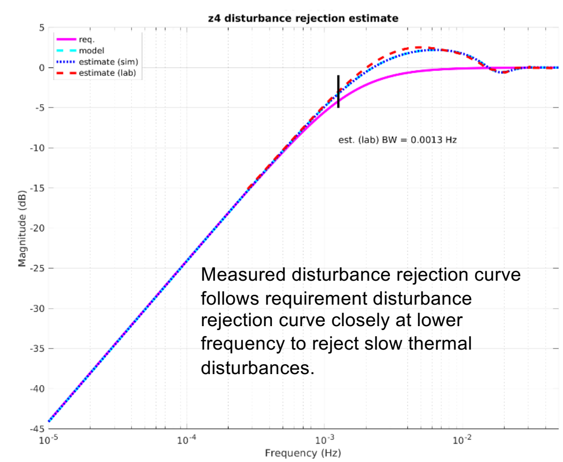








Metric	Requirement	Z4 Design	Z4 Estimate
Disturbance rejection bandwidth (Hz)	0.0016	0.0013	0.0013
Gain margin (dB)	> 6	14	13.8
Phase margin(deg)	> 30	75	69
Delay (sec)	20	20	20



Z5-Z11 (Zernike Loop) rejection

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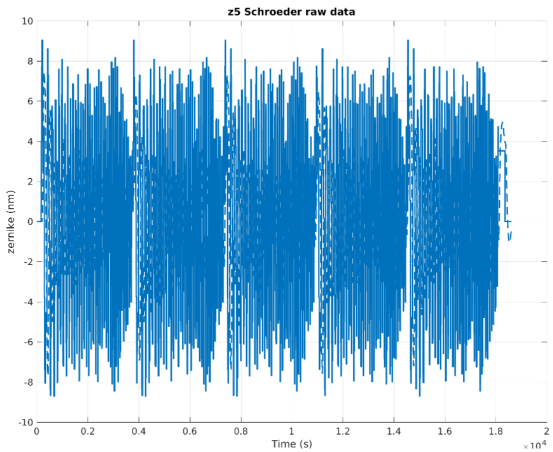
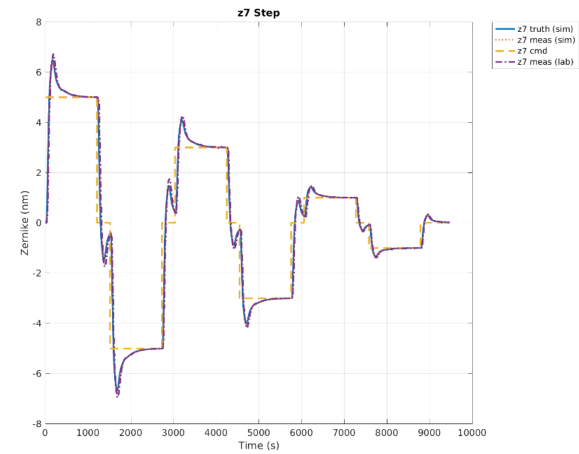
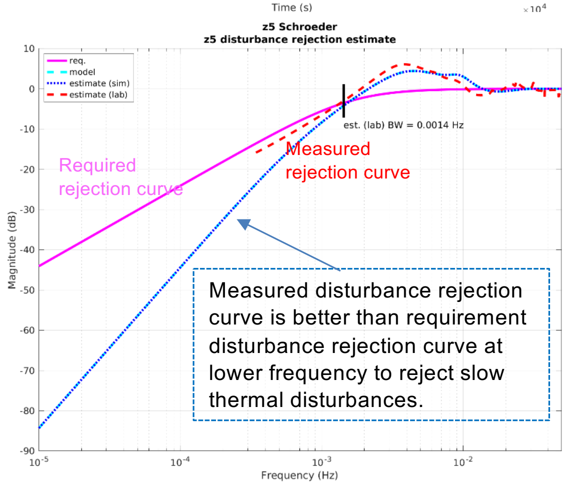
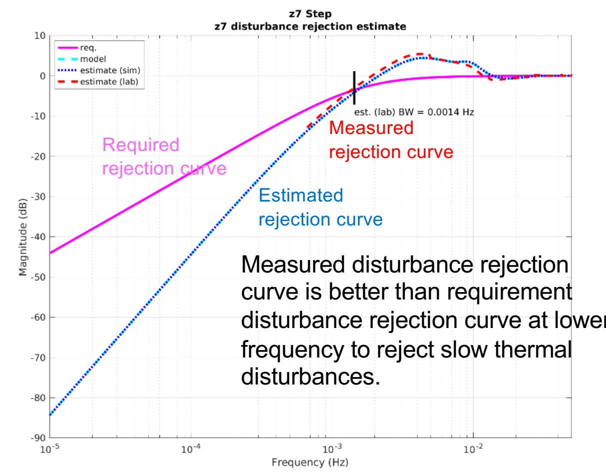




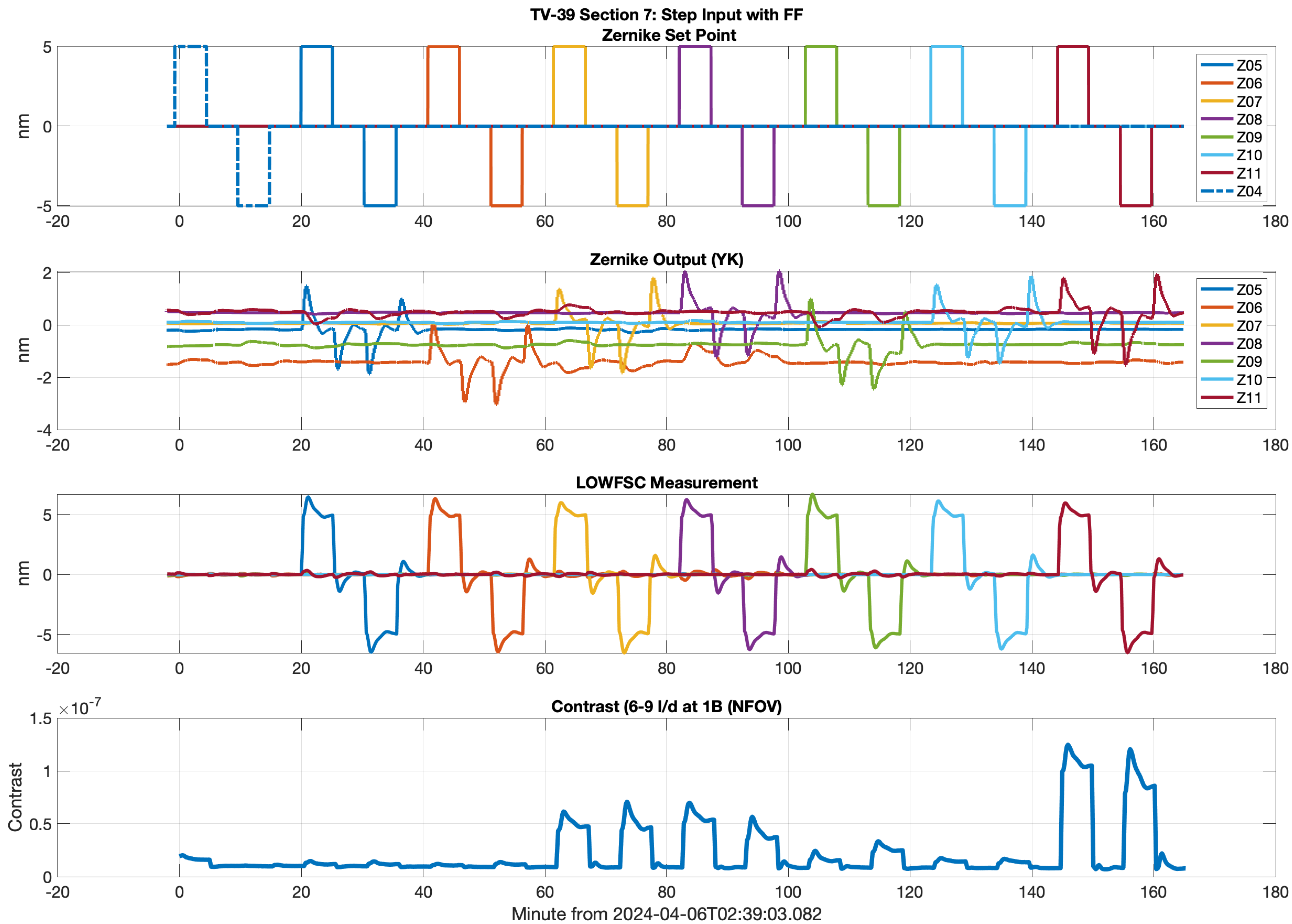


Metric	Requirement	Z5-Z11 Design	Z5-Z11 Estimate
Disturbance rejection bandwidth (Hz)	0.0016	0.0016	0.0014
Gain margin (dB)	> 6	9.5	9.5
Phase margin (deg)	> 30	46	43
Delay (sec)	< 20	14.33	15.5 median



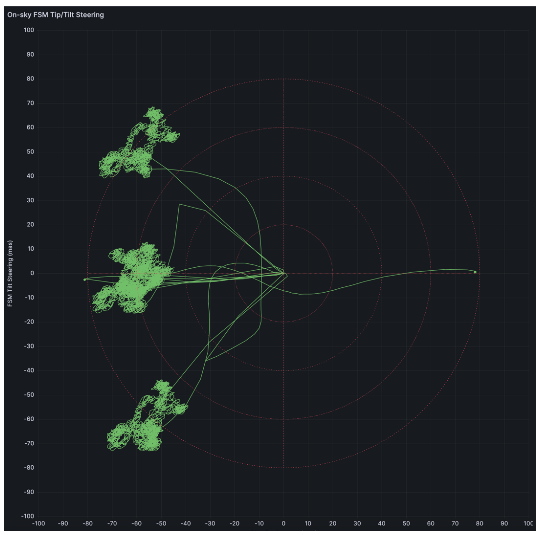
All loops closed, with dark hole measurements

- A variety of data were taken with all loops running, while EXCam was observing a "good dark hole" solution
  - These would be ideal for determining "truth" of LOWFSC stabilization of contrast
- The analysis of these data is complicated by challenges with EXCam flux normalization
  - These tests were determined to be out of scope for requirements verification
    - Activities funded by overguide testing
- Data taken in flight will be the relevant test

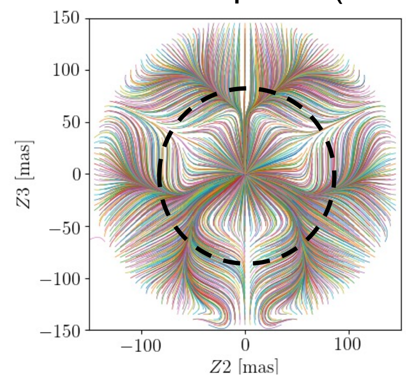


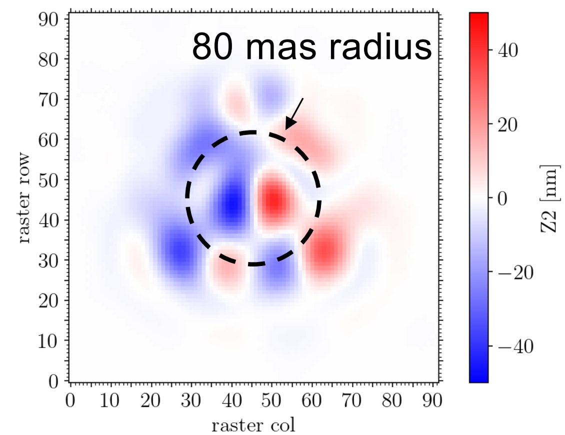
LOWFSC capture range (pointing)

LOWFSC capture (tip-tilt) is complicated by nonlinearity of estimator (FPM phase away from on-axis)



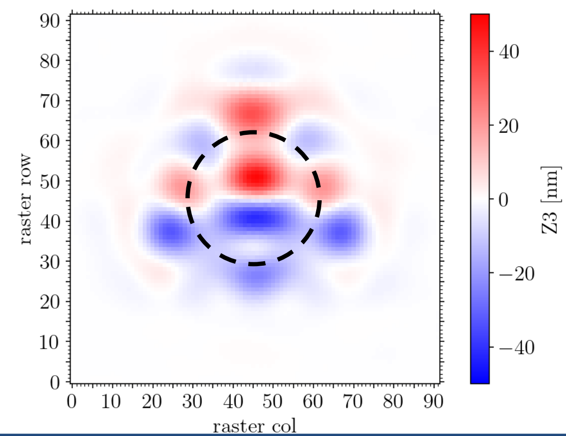
path taken during LOWFSC capture (model)





Tests involved positioning the star at different points on the FPM, and closing the LoS loop.

The most interesting test results show “slow” capture at FPM locations where Z2-Z3 estimates are weak, but eventual capture



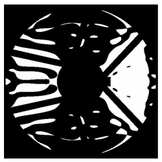
capture tests were successful

4.8 mas / row or col; 80 mas = 17 rows or cols

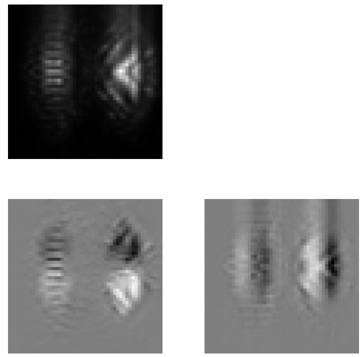
Spectroscopy and Wide FoV configuration

shaped pupil mask

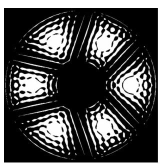
LOCam images



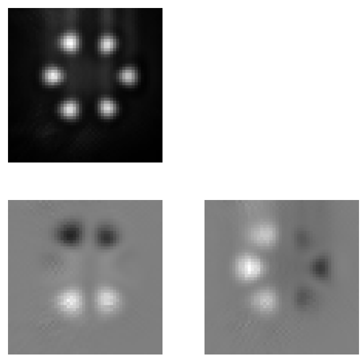
spectroscopy



modes higher than tip-tilt were not exercised on shaped pupil configurations



Wide FoV

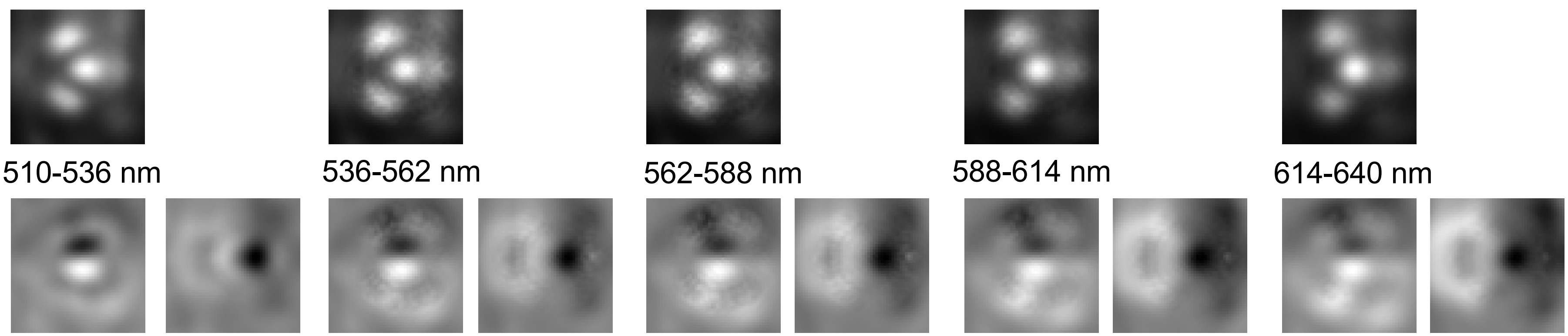


WFoV operated with tip-tilt loop closed during a full shift of HOWFSC testing, no surprises

reasonable confidence LOWFSC will function in shaped pupil configurations

performance requirements verified by analysis

- Crosstalk and pointing repeatability are dominated by chromatic effects
  - LOWFSC is “trained” on a blue reference star
    - reference star spectral types O-B
  - calibration data from a blue reference star are used on red target star
    - target star spectral types F-G-K
  - across 128 nm-wide band, ratio of short-to-long wavelength spectral density changes by ~ 2× for change in spectral type
- for the same PSF centration and WFE, LOWFSC image morphology is different on red star vs blue star
  - changes both in zero-point and in differential mode morphology
- for CVS + NKT spectral input, only short- and long-wavelength cutoff are controlled
  - Test-As-You-Fly exception that we cannot test the operational concepts with flight-like stellar spectra



model validation not yet performed

Summary

- LOWFSC system meets performance requirements on disturbance rejection, LOWFSC capture range
  - Several L4 LOWFSC requirements were verified by analysis
  - Loops did not diverge under “flight-like” operational conditions
- More detailed stability experiments were not conducted in TVAC due to uncertainties associated with TVAC environment, CVS and light source variability and lack of detailed monitoring
  - Out of scope of requirements verification
  - Some model verification data collected but not yet quantitatively compared